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Abstract

An approach to energy systems modelling is presented. It employs a mixture of non-linear programming techniques considered suitable for the particular structure of energy models, in order to overcome the problems encountered in optimisation with a non-trivial objective function topology, e. g. with several local minima. Preliminary results for a European energy model are presented.

Cover illustration: Bent Sørensen: Australian sun

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Abstract

An approach to energy systems modelling is presented. It employs a mixture of non-linear programming techniques considered suitable for the particular structure of energy models, in order to overcome the problems encountered in optimisation with a non-trivial objective function topology, e.g. with several local minima. Preliminary results for a European energy model are presented.

Keywords
Energy systems, energy modelling, non-linear optimization, optimization algorithms

Biographical notes
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1. Introduction: outline of problem

The use of linear programming methods to optimise energy supply systems faces problems in describing some existing and several emerging multi-input/multi-output energy conversion devices, such as combined power and heat plants and reversible fuel cells. Current linear programming energy system models, e.g. MARKAL [1], use little realistic models to get approximate solutions for these types of systems characterised by multi-dimensional optimisation domains in parameter space. The present study explores the possibility of a direct attack on the non-linear system. The following sections describe the type of systems aimed at, the kind of objectives that decision-makers find interesting, and the algoritms selected for solving the problem. Finally, a simple example of numerical calculations is given.

2. Energy system models

Energy systems can be described as networks comprising a number of components broadly classified as energy conversion devices, transmission lines and storage facilities. The inputs are energy sources extracted (e.g. fossil fuels) or collected (e.g. wind energy), and the outputs are end-uses or demands, characterized by temporal and spatial variation. The actual end-use is rarely in the form of energy, and thus end-use devices may comprise a range of different kinds of systems converting energy into the service or product actually demanded.

Each device will typically have inputs of a number of energy forms, and output of a number of energy forms, either the same or ones that are different from those at input. This is true of converters and storage systems, whereas transmission systems (transports, pipelines for gas or district heat, and electric transmission) usually deliver the same energy form as the one input [2]. For energy storage, the form of energy stored may differ from both inputs and outputs [3].

The system model may be a model of an actual system with a limited number of converters, some of which may perform the same function at different locations, or it may be an aggregated model, where similar devices are lumped together (e.g. all coal-fired power plants), thus averaging out any differences between the individual converters.

3. Goals of modelling

The issue is to determine what quantity should be optimised. Typically, it is a cost or another performance measure that often is or could be stated in monetary terms. The main categories of objectives are related to dispatch optimisation and to system planning optimisation.

For dispatch models the system components are considered fixed, and their costs are not entering the quantity to optimise, but only running costs such as fuel purchases and O&M expenses. Demand would be determined exogeneously, by a deterministic or stochastic algorithm or by employing series of actual data.

For the planning models, both installation costs and time constraints such as construction times are important. Here it may also be considered, that some conversion devices may influence the demand, e.g. due to their end-use conversion efficiency being higher than that of the current stock, or due to their augmented convenience in use inducing additional demand.

System delimitations are generally important. If the system is isolated, reserve power capacity may be required, whereas for a system with grid interconnections to other systems outside the modelling area, there would be import and export opportunities, that could play an important role in determining the optimum system layout.

The policy aspect of a planning model makes it important to present different types of policy options in a fair way. Both the selection of these alternatives and the assumptions introduced are important sources of possible bias. The method used for dealing with these questions is typically the scenario method [4], at least if more than a marginal modification of an existing system is aimed at.

The "cost" to be minimised could be the direct cost, but could also comprise externalities calculated according to given prescriptions [5]. Even for modelling of future systems, where some components may have costs that are poorly known, gross cost figures could be used or replaced by "rankings", and repeated calculation could exhibit the influence of uncertainty.

4. Non-linear optimization techniques

Collecting the quantities to vary in a vector $\mathbf{x}$, the minimum of an objective function $f(\mathbf{x})$ may be found by the method of steepest descent [6,7]. It is an iterative method, starting with some variable set $\mathbf{x}_0$ and determining each iterative set

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \lambda_k \mathbf{d}_k, \text{ where } \mathbf{d}_k = -\nabla f(\mathbf{x}_k),$$

by determining the λ_k that minimizes

$$\theta_k(\lambda_k) = f(\mathbf{x}_k + \lambda_k \mathbf{d}_k)$$

in the interval $\lambda_k \in (0,\varepsilon)$, where ε should be chosen (by experience!) small enough to ensure that only one minimum is found in the interval. The iteration is stopped when $\|\mathbf{d}_k\|$ is sufficiently small. The problem with this approach is that it may end up in a shallow local minimum. In neural network theory this is avoided by adding noise to the function f. For the present type of problems, where optimization has to be performed say for hourly intervals over a year, this method is generally too slow. Instead, it may be suggested to replace the differential gradient by a difference gradient $\mathbf{D}_k(\delta)$ defined by

$$\mathbf{D}_k^{(i)}(\delta,\mathbf{n}) = -(f(\mathbf{x}_k+\Delta\mathbf{x}_k) - f(\mathbf{x}_k))/\Delta x_k^{(i)} \quad [\text{i labelling the components of } \mathbf{x}_k],$$

where $\|\Delta\mathbf{x}_k^{(i)}\| = \delta$ and $\mathbf{n} = \Delta\mathbf{x}_k^{(i)}/\delta$, and then vary δ and $\mathbf{n}$ in steps (e.g. $\delta_j = j\,\delta_0$, $j=\{1,m\}$ and the direction $\mathbf{n}$ similarly varied through a finite number of cases p, for each j), and select the set $(\delta_j,\mathbf{n}_p)$ with corresponding

$$\mathbf{x}_{k+1} = \mathbf{x}_k + \mathbf{D}_k(\delta_j,\mathbf{n}_p)$$

for which $f(\mathbf{x}_k + \mathbf{D}_k(\delta_j,\mathbf{n}_p))$ is smallest. By including sufficiently large δ_j's (i.e. large m in the example of equidistant values), local minima may be avoided. Of course, $\mathbf{x}_{k+1}$ must stay within any limits that may be imposed on the parameters. The procedure is illustrated in Fig. 1.

5. Dispatch algoritm

For optimizing the match between supply and demand in a given network of components, supply from units that cannot be varied (wind turbines, solar collectors, and similar devices) is first calculated and dispatched to demand (using the cheapest intermediate converters, where there is a choice). If this gives more energy of some forms than is demanded, these are set aside to be exported, at whatever price may be obtained, or if no export options are available, they are dumped in the cheapest way (either at the initial producing device or later, possible entailing a cost, such as for electric power dump loads).

The remaining energy input devices can be varied within certain limits (hydro power plants, fuel-based converters), as can the outputs of intermediate convertion devices. They are assumed to be described by some kind of ranking (e.g. price of operating), defining the order in which they should be used, for alternatives capable of delivering a given form of demanded energy. The optimization described in section 4 is to be carried out for the conglomerate of all devices in the system, at each step, due to possible interconnectivity, either because of multiple inputs or outputs, or because of device inter-connections. The parameters defining the path and speed of optimization (the δ_j and $\mathbf{n}_p$ mesh described above) may have to be adjusted for a given system under investigation. The outcome may involve unplanned imports and exports, even if these have the lowest rankings or highest costs.

The result at convergence is an optimum dispatch of the available devices, for a given time with its defined demands. The procedure is a bit more complicated, if energy stores are part of the system, because then it has to be deceided whether use of the stores (with their cost and capacity limits) is preferable to using imports/exports, or to varying other available devices. The simplest modelling attaches a cost to the storage devices, which depends on actual use, and costs related to the amount of energy stored, and to filling and extraction rates and amounts. This allows the optimization to be carried out for each time step. It does not catch the possibility, that long-term storage management may offer or require new control options. For example, if there are start-up costs associated with some of the devices, a smoothed operation can be advantageous, and there would be storage operation strategies that best capture such benefits. In terms of modelling, this is an added complication, that forces the modeller to consider a number of time steps (given by the storage capacity in the system) at the same time, as part of the space of variations.

6. Dynamic systems algoritm

In the case of system investigations, the objective function should include also the capital costs of system components, possibly including externalities ("social costs" as evaluated e.g. in a life-cycle analysis [5]). Externalities could also comprise items such as financing restraints, which may be different for alternative system devices serving the same purpose. The dynamic modelling of an energy system can take into account time lags, but cannot generate the development of demand, as this involves not only the interplay with the system's efficiency of energy supply, but also the development of society as a whole, including non-energy economic activities and consumer preferences and values. It is customary either to associate energy models with simplified macro-economic models, or with scenarios of future development sufficiently detailed to allow demand forecasts that include the interplay between energy technologies and tasks requiring energy supply.

The technique outlined above would be used at any given time to define the use of the present system. The next step in time would then be calculated using demand and technology forecasts, and the optimization would include installed capacities of all types of devices (supply, conversion, transport and end-use), subject to the limits imposed by manufacturing and construction times. This optimization is in principle the same as for the dispatch case, except that more variables are to be varied. Again import nd export may when available be used to buffer against mismatch between demand and supply caused by the inherent lead times. The following time steps are performed successively, each departing from the optimized system of the preceding time step.

There are alternatives to this procudure. One is to make a scenario of demand in a distant future, optimize the supply and distribution system for this situation, and then work backwards towards the present system, by "subtracting" system components under consideration of their lead times and possible cost changes as function of time. System components of the current system are kept alive for the period of time needed (with reasonable consideration of component life times, quantities always somewhat uncertain and depending on the level of operation, maintenance and repair costs), and in this way those scenarios that may emerge smoothly from the present one are singled out, as well as those for which no consistent path from the current situation exists. This procedure will normally require the final scenario year to be sufficiently close to the present to limit the system component exchanges to one (i.e. that a given piece of equipment will be replaced once and no more). If multiple component replacements are to be represented, the procedure will have to be modified to accomodate this.

As in the dispatch case, energy storage poses additional problems, because of its time perspective. However, if the system simulation uses time steps of sufficient length (typically a year or more), the storage treatment can be done as in the dispatch case (just including the capital cost of storage) and will not couple the calculations for different time steps.

7. Examples of simulation

A simplified example of using the above methodology will now be presented, based upon a computer program called NESO [8], that in its final form will include all of the methods described above, but which at present is considerably restricted relative to this goal. The current version first calculates the demands and source energy productions of a given system or scenario, and then chooses intermediate conversions on the basis of a simple ranking of devices (as a reflection of operational costs). Transmission is not explicitly modelled but incorporated into the demand for different energy forms, increasing them by the assumed losses in transmission. For the primary energy production, a minimum and a maximum is calculated. These are identical for wind and solar devices, but may be different for fuel based (fossil or biomass) or hydro systems, where the production can be regulated (from zero or some minimum flow to a maximum depending on rated capacity). Primary conversion into methanol, biogas or hydrogen is included in the source calculation.

The production is distributed on energy forms (low- and high-temperature heat, electricity, gaseous and liquid fuels), and the maximum of each energy form already suited for covering demand is allowed to do so. Regarding the rest, it is attempted to convert the remainder of the energy produced to the energy forms in further demand, by going through the intermediate converters in the order of their assigned priority (fuel cells, CHP, heat pumps, furnaces, boilers). Energy storage is not modelled in this version, but any deficit in covering loads, or surplus of energy than cannot be made useful, is noted, for each hour and acculated over one day, a month or a year. This allows the analysis of storage requirements, because one will know the maximum required capacity from the maximum power drawn in one hour (or one may omit extremes if they happen rarely, assuming that they are covered e.g. by gas turbines in case of electric power). Comparing the hourly deficit/surplus with the daily averages, one can assess the effect of diurnal storage, and similarly the difference between daily and monthly imports and exports will indicate the effect of a monthly storage facility.

The sources that can be regulated are characterized by their range of regulation. This allows modelling of some storage problems, as the range of regulation for fuel-based primary converters can be interpreted to involve storage as well as fuel-backup.

The simulations are based on a fair market scenario for Western Europe for the year 2050, developed in a project for the European Commission [9]. It is a market scenario in the sense that the choice of system components is based on lowest cost. It is further a "fair" market scenario, because the costs assumed in the system choice include externalities [5,10]. The most significant and controversial externality in the case of fossil fuels is the greenhouse warming impact. It has been calculated on the basis of the damages identified by the most recent assessment of the Intergovernmental Climate Panel [11], using globally a statistical value of life equal to 2.6 million ECU, as derived in a recent EC externality project [12]. Details of the monetising calculation is contained in [10]. The energy system layout, which is one policy option for the European Union in the year 2050, is summarized in Fig. 2.

The average demands and supplies are overlayed with time variations. For the demands, the winter low-temperature heat load is rising to twice the average, while the summer usage is 20% of the annual average (hot water use, according to scenarios). No variations during the day are included, assuming each user to have at least a water storage tank capable of smoothing the diurnal variations in load. For high-temperature heat, the load is assumed to be 20% higher than average during work hours and 10% lower outside work hours, assuming the usage in many industries as being continuous. The same is true for use of gaseous fuels, with variations between 110% and 95%. For transportation liquid fuels, no variations are considered, assuming that vehicle gasoline tanks and filling station storage will take care of diurnal and seasonal variations, respectively.

On the source side, wind power production is modelled through a Weibull distribution of wind speeds (with parameters k=2.4 and c=6 and 8 for on-land and off-shore turbines, respectively). Wind speeds are selected stochastically from this distribution, but then subjected to a 50% correlation with the wind speed for the previous hour. The power production is derived from the wind speed by using a standard wind turbine power curve, with cut-in speed 5.5 m/s and reaching rated power at 12 m/s. Hydro power is taken at average scenario value, but with a factor of 0.5 to 1.5 variation made possible, as a reflection of the regulation possible for the reservoir-based fraction of hydro systems in Europe. This should be seen as an average between run-of-the-river systems and reservoir-based systems with varying regulation capacity. For solar radiation, a distribution is used which has a diurnal and seasonal sine squared distribution overlayed with 50% stochastic noise. The diurnal distribution takes care of the length of day in different seasons and the seasonal factor varies between zero and one, corresponding to an average European location. For solar thermal power, a different length-of-day distribution is used, considering these installations to be placed only in Southern Europe. In all cases, a 20% correlation with the previous hour is built in.

All other sources are modelled by the scenario efficiency of primary conversion, just as the intermediate conversions from one energy form to another use the efficiencies estimated in the scenario for future technology. The production of gaseous and liquid biofuels may vary within limits of 10-40%, in order to follow variations in direct demand for these fuels, but the overdrawing limited in such a way, that the annual average use is staying at the scenario values.

Figs. 3-6 gives the simulation results for year 2050 deficits and surpluses of low-temperature heat and electricity on an hourly basis, for the months of january and july (there are no deficits or surplusses for the other energy forms). Fig. 7 gives annual summaries, not just of deficits and surplusses, but also the range of possible production from the sources, plus the actual production, the load, and the energy supplied to intermediate conversion devices. The surplusses and deficits shown give the results after intermediate conversion between energy forms, whereas the "actual production" is the production of each energy form before "reshuffling". The intermediate conversions are the inputs to each conversion device.

It is seen, and could be expected, that there is a deficit of heat during winter and a slight surplus in summer. For electricity, there are patterns of occasional deficits and surplusses throughout the year, but with highest deficits in winter and highest surplusses in summer. This reflects the intermittency of wind power and the seasonality of all solar-based energy production. The electricity deficits are assumed to be covered by imports from Norwegian hydro, solar power from North Africa or other electricity. The deficit in heat during winter is a serious problem, as it is persistent and cannot be remedied by diurnal or monthly stores. Thus, there has to be either seasonal storage of heat or fuel-based backup. In the EC study, fuel-based additions are selected as the solution, because they can be achieved without violating the scenario conditions of 80% reduction in greenhouse gas emissions.

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Figures:

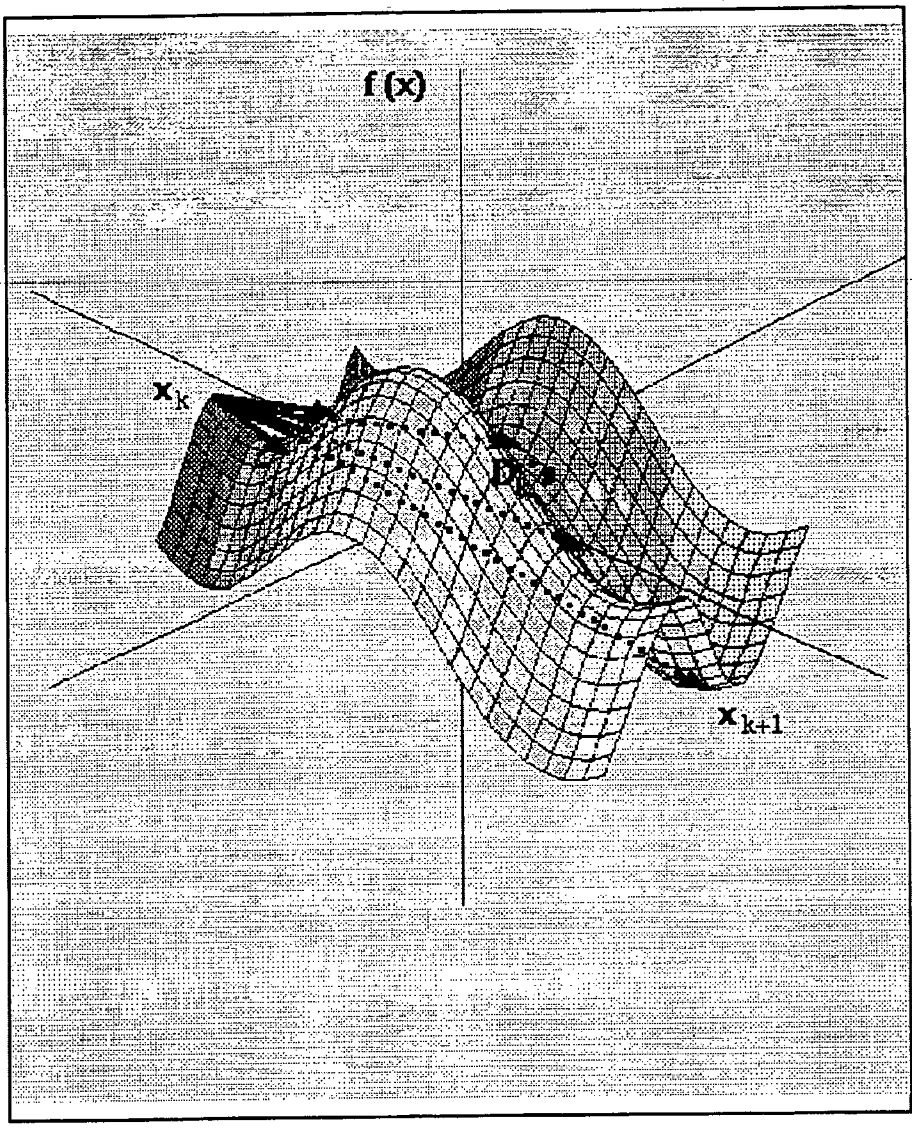

Figure 1. Schematic illustration of optimization procedure (see text).

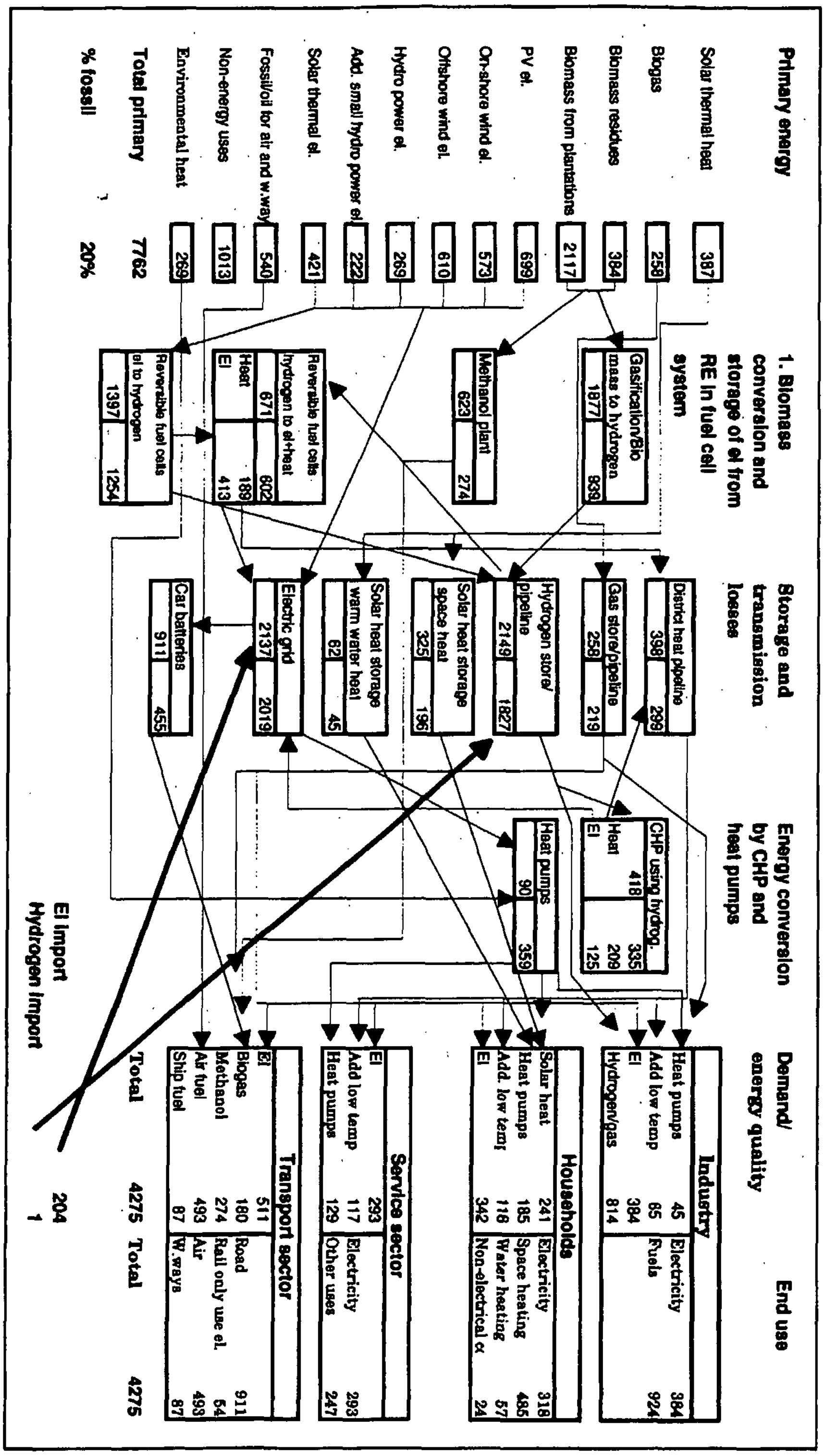

Figure 2. Summary of energy conversion system for a fair market scenario of the 15 EU countries, by year 2050 (unit: Twh/y) [9]

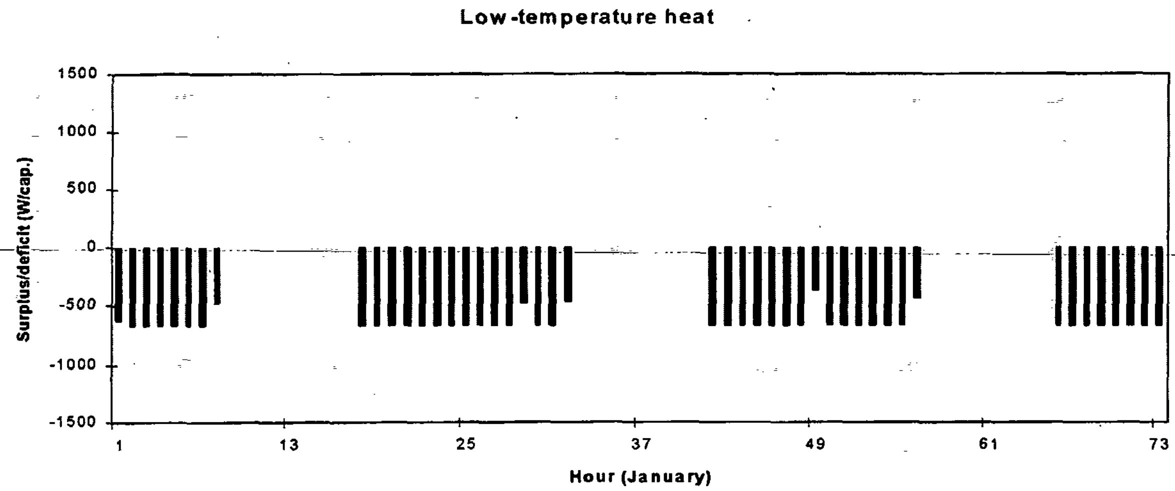

Figure 3. Predicted deficit of low-temperature heat during three january days, for the model depicted in Fig. 2.

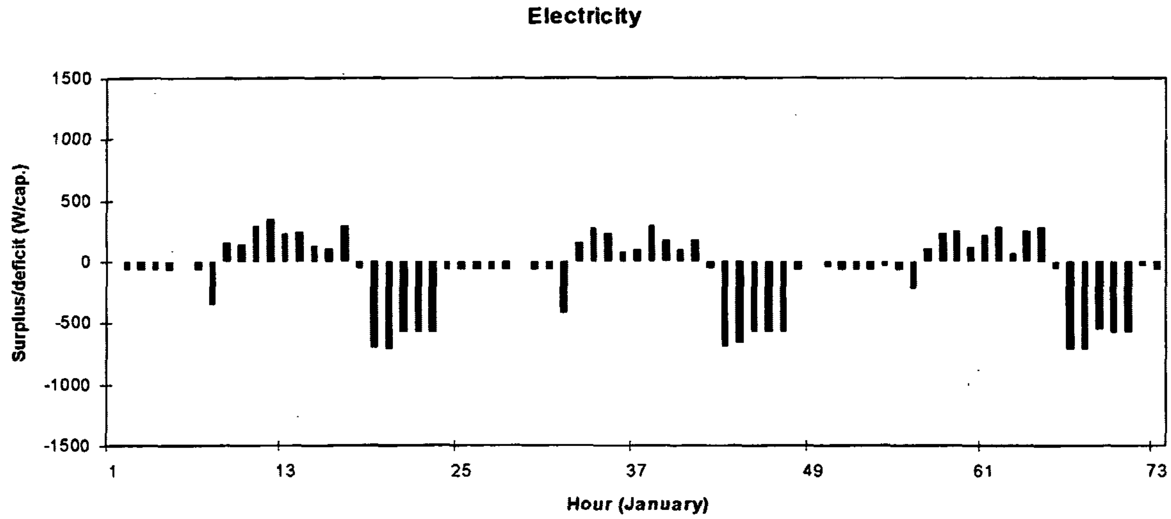

Figure 4. Predicted surplusses and deficits of electricity during three january days, for the model depicted in Fig. 2.

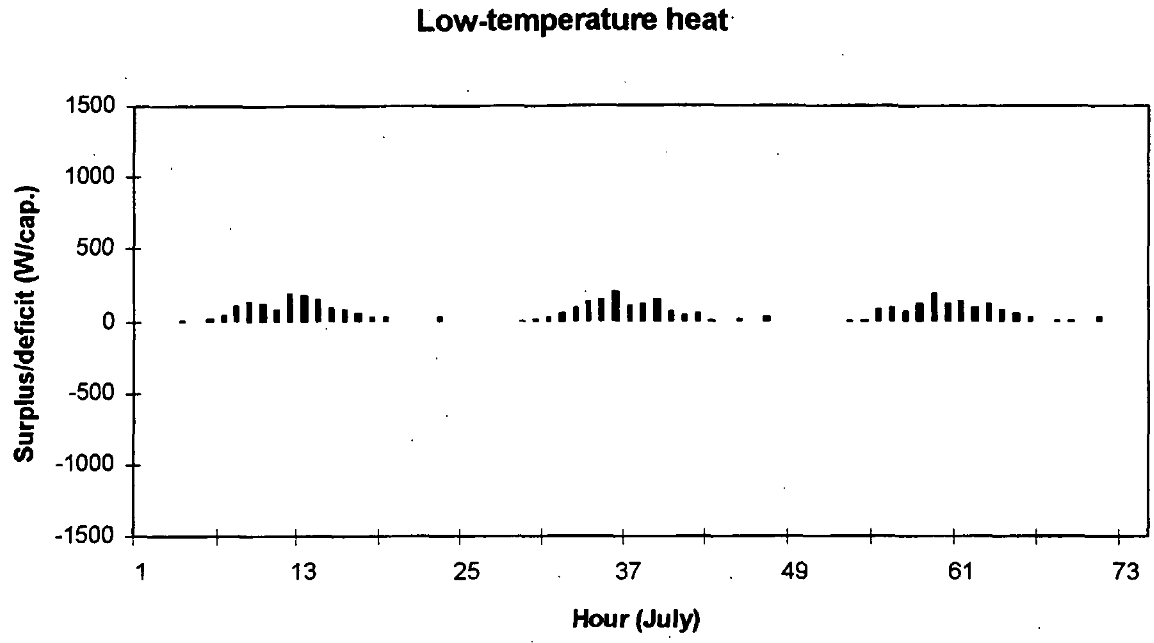

Figure 5. Predicted surplus of low-temperature heat during three july days, for the model depicted in Fig. 2.

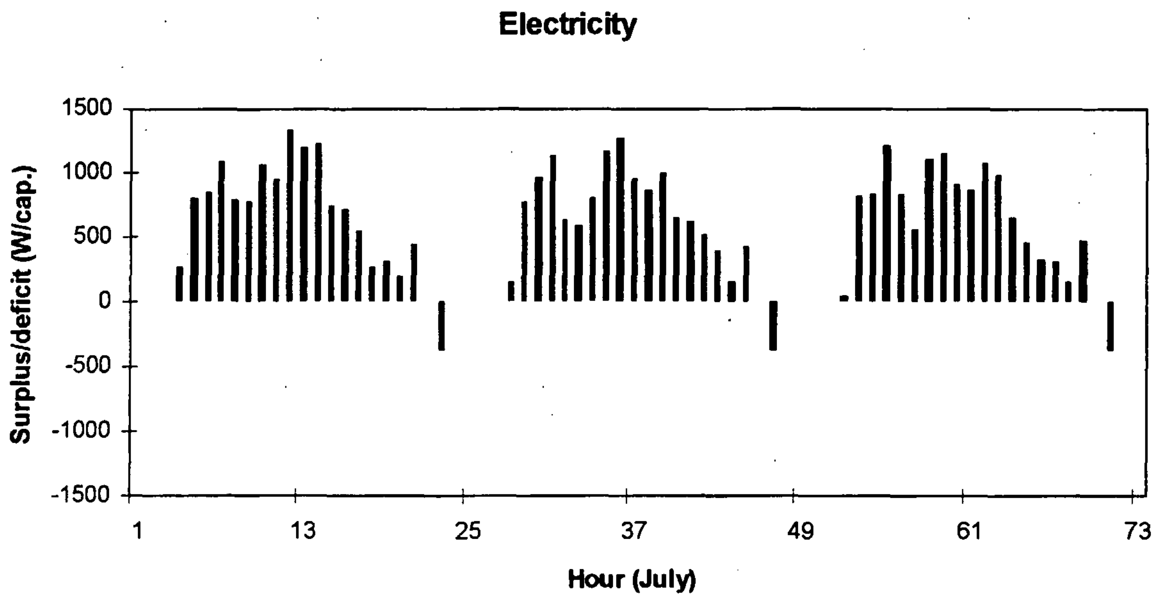

Figure 6. Predicted surplusses and deficits of low-temperature electricity during three july days, for the model depicted in Fig. 2.

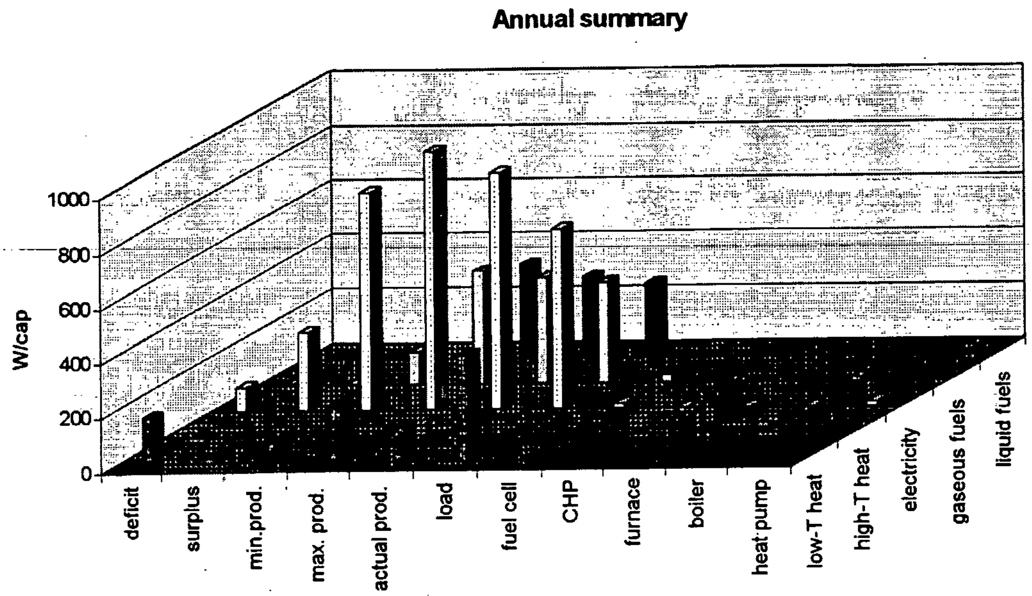

Figure 7. Summary of hourly simulations of European year 2050 energy system through one year. The columns to the right represent conversion to the energy form indicated, whereas the columns labelled "actual production" indicate direct production of the energy form in question. The deficit and surplus columns are import needs and export potentials after all energy conversions have taken place.

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246/93 HVERDAGSVIDEN OG MATEMATIK - LÆREPROCESSER I SKOLEN

af: Lena Lindenskov, Statens Humanistiske Forskningsråd, RUC, IMFUFA

247/93 UNIVERSAL LOW TEMPERATURE AC CONDUCTIVITY OF MACROSCOPICALLY DISORDERED NON-METALS

by: Jeppe C. Dyre

248/93 DIRAC OPERATORS AND MANIFOLDS WITH BOUNDARY

by: B. Booss-Bavnbek, K.P.Wojciechowski

249/93 Perspectives on Teichmüller and the Jahresbericht Addendum to Schappacher, Scholz, et al.

by: B. Booss-Bavnbek

With comments by W.Abikoff, L.Ahlfors, J.Cerf, P.J.Davis, W.Fuchs, F.P.Gardiner, J.Jost, J.-P.Kahane, R.Lohan, L.Lorch, J.Radkau and T.Söderqvist

250/93 EULER OG BOLZANO - MATEMATISK ANALYSE SET I ET VIDENSKABSTEORETISK PERSPEKTIV

Projektrapport af: Anja Juul, Lone Michelsen, Tomas Højgård Jensen

Vejleder: Stig Andur Pedersen

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by: Freddy Bugge Christiansen, Viggo Andreasen and Ebbe Thue Poulsen

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Projektrapport af: Birthe Friis, Lisbeth Helmgaard, Kristina Charlotte Jakobsen, Marina Mosbæk Johannessen, Lotte Ludvigsen, Mette Hass Nielsen

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Teori og model

af: Lise Arleth, Kåre Fundal, Nils Kruse

Vejleder: Mogens Niss

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af: Peter Harremoës

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af: Mogens Brun Heefelt

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Eksamensopgaver fra 1976-93

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To Sigurdur Helgason on his sixtyfifth birthday
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Fysikspeciale af: Anja Boisen, Peter Bøggild, Karen Birkelund
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